Recent EFT measurements from ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations

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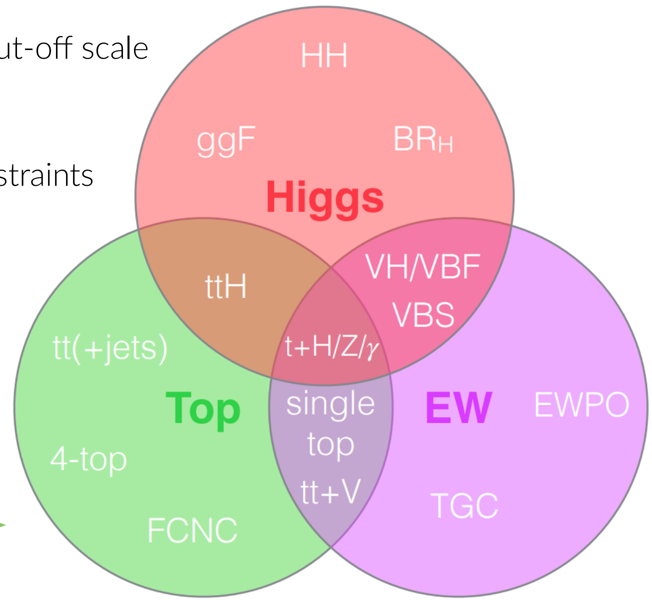
Introduction

- So far no evidence of new physics (NP) from resonance searches
  - Search indirectly for NP using precision measurements of known processes

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i,d>4} \frac{c_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)}$$

- Standard Model Effective Field Theory (SMEFT) can be used to parametrise deviations in terms of higher dimensional operators
  - Variety of possible bases, e.g. Warsaw, Higgs, HISZ, etc.
  - Higher order terms suppressed by increasing powers of cut-off scale
  - Reject B/L violating dim. 5 and dim. 7 operators
  - Lowest order is then dim. 6, but some analyses place constraints on dim. 8
- Measurements may be direct or use reparametrisation
  - Direct measurements fully take into account acceptance/efficiency effects, but implementation can be harder
- Focus today on recent* EWK, Higgs and Top measurements
  - Distinction sometimes arbitrary
  - Many processes affected by same operators



K. Mimasu

*since previous meeting (October 2020)

Contents

Electroweak measurements

$pp \to 4l$, $W\gamma$, WW, WZ, $V\gamma\gamma$, $Z\gamma jj$

Higgs measurements

$H \to 4l$, $H \to \gamma\gamma$, Higgs combinations

Top measurements

$t(t)$ + leptons, $tt\gamma$

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Electroweak measurements

$pp \to 4l, \quad W\gamma, \quad WW, \quad WZ, \quad V\gamma\gamma, \quad Z\gamma jj$

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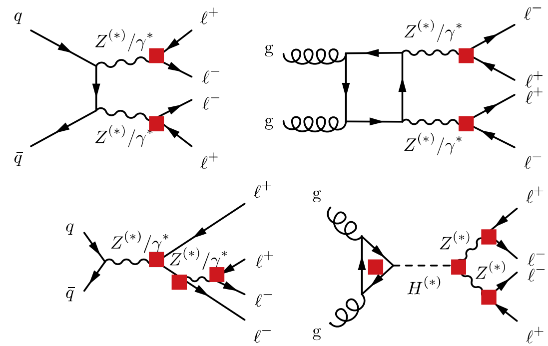
Top measurements

$t(t)$ + leptons, $t t\gamma$

$pp \to 4l$ ATLAS EXPERIMENT

139 fb^{-1} [arXiv:2103.01918]

- **Multiple SM processes contribute to 4*l* final state** →



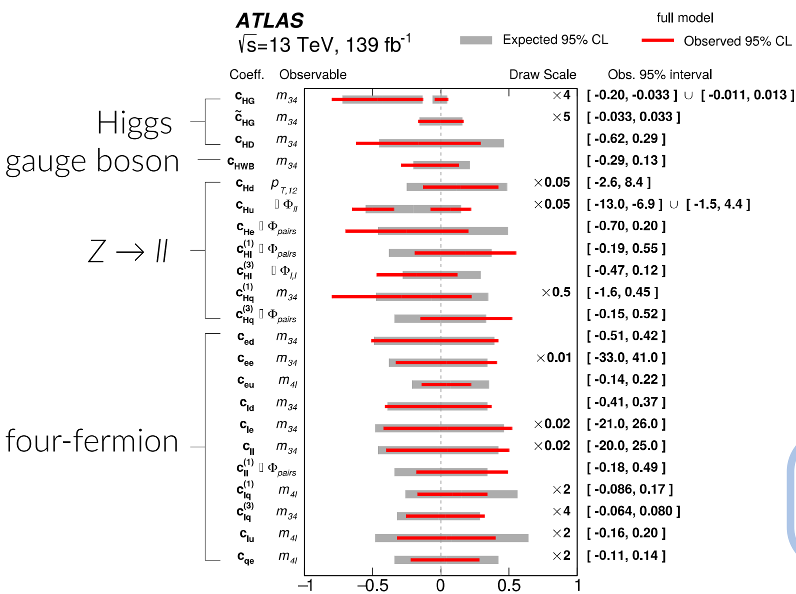
  - $m(4l)$ measured double-differentially in $p_T(4l)$ and $|y(4l)|$
  - Additionally range of kinematic/angular variables measured in four $m(4l)$ regions → used to constrain EFT coefficients

- **EFT limits set with likelihood function for unfolded distributions:**

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp\left\{-\frac{1}{2}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}\left(\vec{\theta}\right)\right]^T C^{-1}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}\left(\vec{\theta}\right)\right]\right\} \times \prod_i \mathcal{G}\left(\theta_i, 0, 1\right)$$

$$\vec{\sigma}^{\text{pred}} = \vec{\sigma}^{\text{SM}} \times \left(1 + c_i \cdot \vec{\sigma}^{\text{INT}}/\vec{\sigma}^{\text{LO SM}} + c_i^2 \cdot \vec{\sigma}^{\text{BSM}}/\vec{\sigma}^{\text{LO SM}}\right)$$

θ_i = BSM nuisance parameters



- **22 coefficients giving non-negligible contributions considered separately** (setting others to zero)
  - Choose most sensitive observable to set limit (vs. $m(4l)$)
- **Linear and linear + quadratic fits performed**

> **Quadratic terms have significant impact for many four-fermion operators** – smaller impact on some other operators

$W^{\pm}\gamma$

137 fb^{-1} [SMP-20-005]

- **Interference term can be suppressed** due to different helicity configurations of SM and BSM contributions [arXiv:1708.07823] [arXiv:1707.08060]

e.g.

$$q\bar{q} \longrightarrow V_{T_\pm} V_{T_\mp} \quad \text{(in the SM)},$$
$$q\bar{q} \longrightarrow V_{T_\pm} V_{T_\pm} \quad \text{(with } O_{3W} \text{ insertion)}$$

  - Leading contribution becomes quadratic term (higher dimension operators may also be important)
  - Choosing suitable variables or phase spaces can overcome helicity suppression → e.g. azimuthal angles of decay products; allowing for jets in the final state

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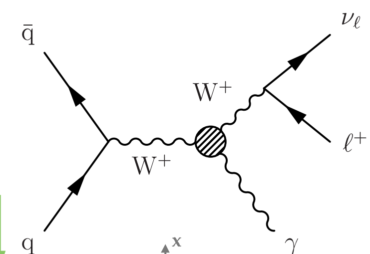
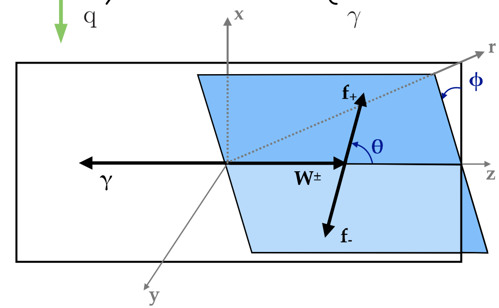
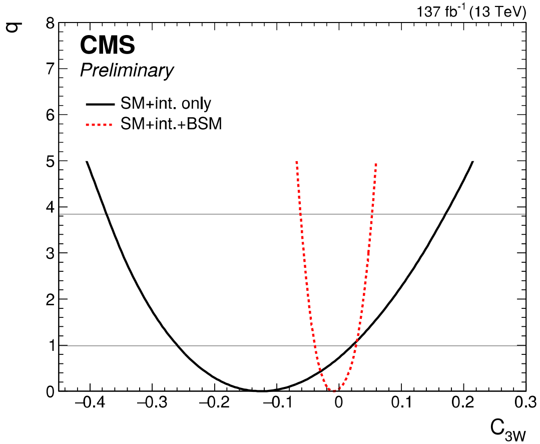
- ***O_{3W}* affects triple gauge boson vertex** → interference term suppressed
- **Sensitivity to linear term increased by measuring differentially in p_T^{γ} x $|\varphi_f|$**
  - Boost to $W\gamma$ rest frame and use azimuthal angle of f^+ fermion = φ_f







- **Maximum likelihood fit performed** with reparametrised cross-sections

$$\sigma_j^{\text{tot}} = \sigma_j^{\text{SM}} + C_{3W}\sigma_j^{\text{int}} + C_{3W}^2\sigma_j^{\text{BSM}}$$

- **Tighter p_T^{l} and p_T^{γ} cuts** than nominal selection, and **jet veto**

Sensitivity to linear term improved by factor of up to 10 with addition of angular variable, but **quadratic term still dominant**

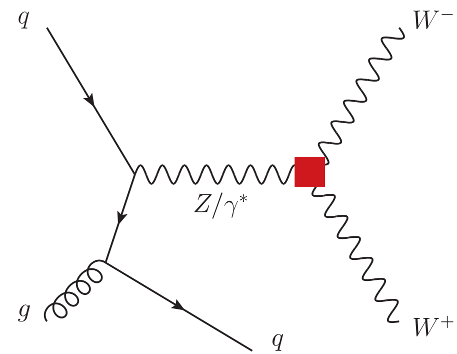
$WW + \geq 1$ jet

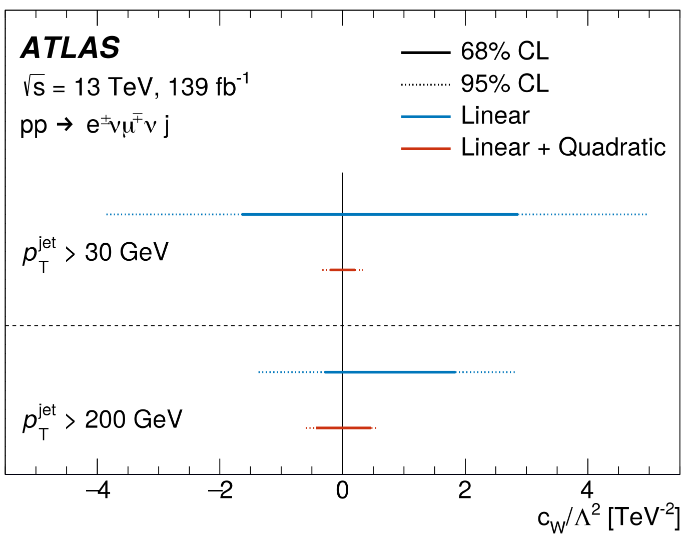
ATLAS EXPERIMENT

139 fb^{-1}

[arXiv:2103.10319]

- **First jet-inclusive differential *WW* measurements at LHC**
- **Sensitivity to c_W** via gauge boson self-couplings
  - Suppression of interference term in jet veto measurement
  - Lift suppression with hard jet → impact of linear term expected to increase with jet p_T [arXiv:1707.08060]
- **Reparametrise unfolded m_{ll} cross section** with Wilson coefficient c_{3W}





- **Maximum likelihood fit performed** in dedicated region with $p_T^{\text{lead.jet}} > 200$ GeV
- **Linear and linear + quadratic fits performed**
  - Linear limits beat same limits from *WW* + 0 jet 36fb^{-1} measurement [arXiv:1905.04242], but behind constraints from *Z* + dijets measurements [arXiv:2006.15458]

Quadratic term still dominant, but impact reduced at higher jet p_T

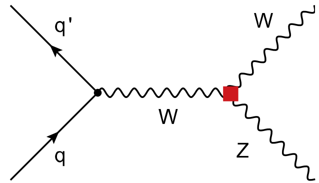
$pp \to WZ$

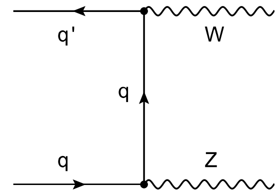
137 fb^{-1} [SMP-20-014]

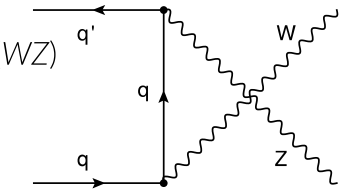
- Fiducial and differential cross sections measured in trilepton final states
- Sensitivity to 3 CP-conserving and 2 CP-violating terms

$$\delta\mathcal{L}_{AC} = \frac{c_{WWW}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + c_W\left(D_\mu H\right)^\dagger W^{\mu\nu}\left(D_\nu H\right) + c_b\left(D_\mu H\right)^\dagger B^{\mu\nu}\left(D_\nu H\right)}{\Lambda^2} + \frac{\tilde{c}_{WWW}\mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + \tilde{c}_W\left(D_\mu H\right)^\dagger \tilde{W}^{\mu\nu}\left(D_\nu H\right)}{\Lambda^2}$$

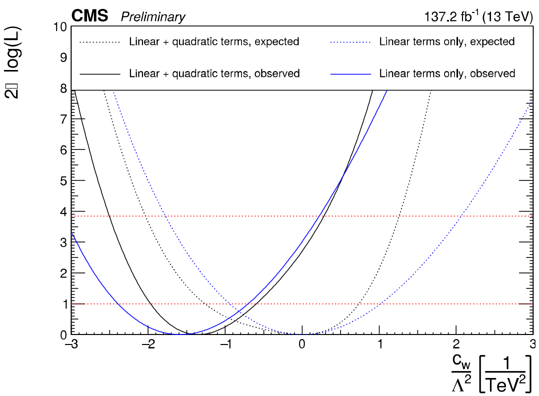
HISZ basis

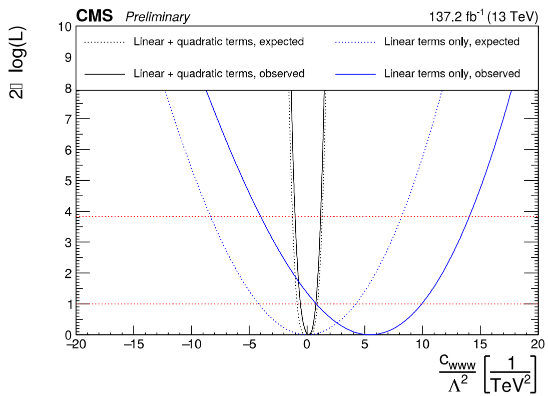


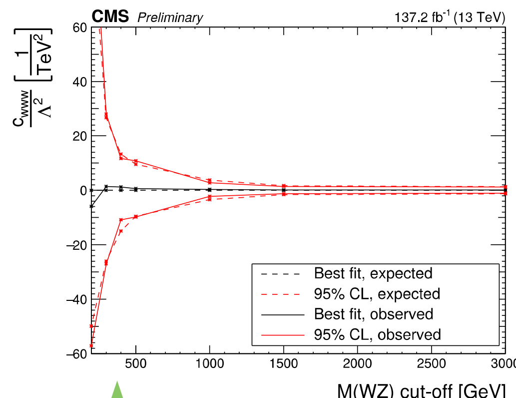




- CP-conserving/violating terms fit separately in linear and linear + quadratic fits with $m(WZ)$







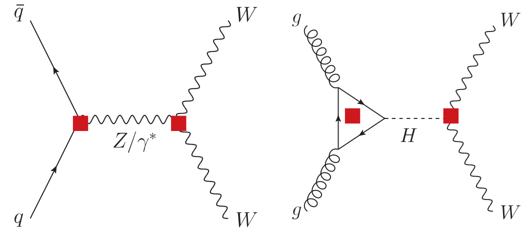
Quadratic term has dominant impact on several coefficients

- Validity of EFT expansion investigated by varying $m(WZ)$ cut-off

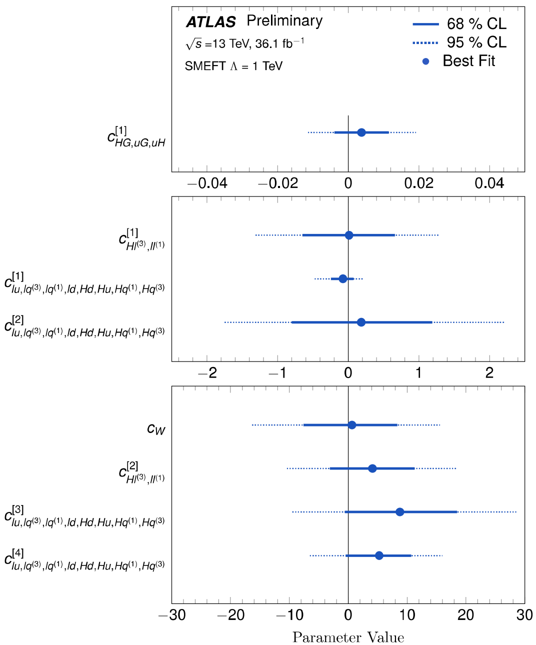
$WW + H(WW^*)$

36 fb^{-1} [ATL-PHYS-PUB-2021-010]

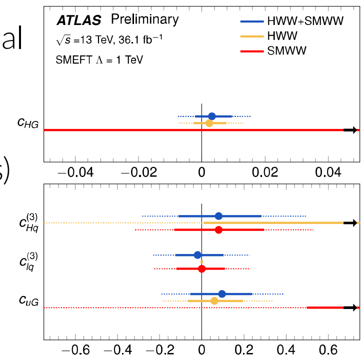
- **Combination of WW + 0 jets and $H(WW^*)$ measurements** [STDM-2017-24] [HIGG-2016-07]
  - Large number of dim. 6 operators affect both processes
  - WW is background for $H(WW^*)$ → estimated in dedicated CR
    → use WW SR in place of $H(WW^*)$ CR



- **Use unfolded WW $p_T^{\text{lead.lep.}}$ distribution** (14 bins) and **$H(WW^*)$ ggF + VBF signal strength modifiers** in likelihood



- **Linearised EFT model** → reparametrise signal strength modifiers in terms of c_i
  - Modifications to $H \to e\mu\nu\nu$ BR also considered (including acceptance effects)
  - Common NPs treated as correlated in combined likelihood



- **Search for sensitive directions**
  - Group 20 CP-even operators according to physics impact → reparametrise Hessian in c_i and find eigenvectors for each group
  - 8 sensitive directions (based on eigenvalues) → fit simultaneously

Agreement with SM at level of 1σ (2σ for individual fits) or better

$V\gamma\gamma$, $Z\gamma jj$

- **Both processes probe dim. 8 operators** → anomalous quartic gauge couplings (aQGCs)

$V\gamma\gamma$ — 137 fb^{-1} [SMP-19-013]

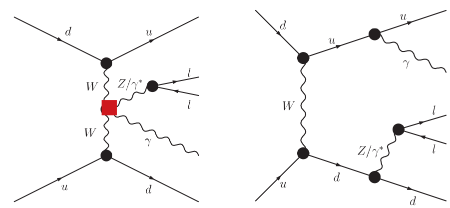
- **Fit 10 coefficients using reparametrised detector level $p_T^{\gamma\gamma}$**
  - aQGC enhanced at high p_T

95% CL

Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	$W\gamma\gamma$ (TeV^{-4}) Observed	$Z\gamma\gamma$ (TeV^{-4}) Expected	$Z\gamma\gamma$ (TeV^{-4}) Observed
$f_{M,2}/\Lambda^4$	[−57.3, 57.1]	[−39.9, 39.5]	-	-
$f_{M,3}/\Lambda^4$	[−91.8, 92.6]	[−63.8, 65.0]	-	-
$f_{T,0}/\Lambda^4$	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
$f_{T,1}/\Lambda^4$	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
$f_{T,2}/\Lambda^4$	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
$f_{T,5}/\Lambda^4$	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
$f_{T,6}/\Lambda^4$	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
$f_{T,7}/\Lambda^4$	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
$f_{T,8}/\Lambda^4$	-	-	[−0.90, 0.94]	[−1.06, 1.10]
$f_{T,9}/\Lambda^4$	-	-	[−1.54, 1.54]	[−1.82, 1.82]

$Z\gamma jj$ — 137 fb^{-1} [SMP-20-016]

Operator coefficients	Expected [TeV^{-4}]	Observed [TeV^{-4}]	Freeze all syst. [TeV^{-4}]	Unitarity bound [TeV]
F_{M0}/Λ^4	-12.5 , 12.8	-15.8 , 16.0	-15.2 , 15.4	1.1
F_{M1}/Λ^4	-28.1 , 27.0	-35.0 , 34.7	-33.8 , 33.3	1.2
F_{M2}/Λ^4	-5.21 , 5.12	-6.55 , 6.49	-6.32 , 6.23	1.4
F_{M3}/Λ^4	-10.2 , 10.3	-13.0 , 13.0	-12.4 , 12.5	1.6
F_{M4}/Λ^4	-10.2 , 10.2	-13.0 , 12.7	-12.5 , 12.3	1.4
F_{M5}/Λ^4	-17.6 , 16.8	-22.2 , 21.3	-21.4 , 20.4	1.8
F_{M6}/Λ^4	-25.0 , 25.6	-31.7 , 32.0	-30.4 , 30.8	1.1
F_{M7}/Λ^4	-44.7 , 45.0	-56.6 , 55.9	-54.3 , 53.8	1.3
F_{T0}/Λ^4	-0.52 , 0.44	-0.64 , 0.57	-0.62 , 0.55	1.4
F_{T1}/Λ^4	-0.65 , 0.63	-0.81 , 0.90	-0.78 , 0.77	1.5
F_{T2}/Λ^4	-1.36 , 1.21	-1.68 , 1.54	-1.63 , 1.48	1.4
F_{T5}/Λ^4	-0.45 , 0.52	-0.58 , 0.64	-0.55 , 0.62	1.8
F_{T6}/Λ^4	-1.02 , 1.07	-1.30 , 1.33	-1.25 , 1.29	1.7
F_{T7}/Λ^4	-1.67 , 1.97	-2.15 , 2.43	-2.06 , 2.36	1.8
F_{T8}/Λ^4	-0.36 , 0.36	-0.47 , 0.47	-0.46 , 0.46	1.5
F_{T9}/Λ^4	-0.72 , 0.72	-0.91 , 0.91	-0.88 , 0.88	1.6



- **Fit 16 coefficients using differential $m_{Z\gamma}$**
- **Limits similar to $W\gamma jj$**

Observations consistent with SM

Contents

Electroweak measurements

$pp \to 4l$, $W\gamma$, WW, WZ, $V\gamma\gamma$, $Z\gamma jj$

Higgs measurements

$H \to 4l$, $H \to \gamma\gamma$,   Higgs combinations

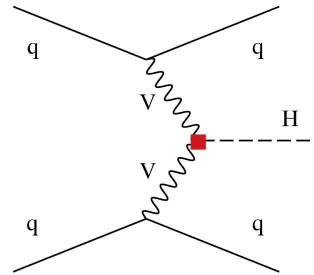
Top measurements

$t(t)$ + leptons, $tt\gamma$

$H \to 4l$

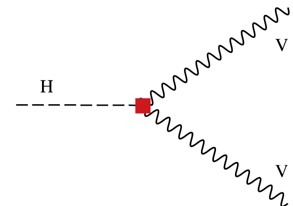
137 fb^{-1} [arXiv:2104.12152]

- **Dedicated EFT measurement** → full MC simulation of new physics, including acceptance and efficiency effects



- **Study structure of *HVV*, *Hgg* and *Htt* interactions** in SMEFT framework
  - *ggH*, *VBF*, *VH*, *ttH*, *tH*, *bbH* production all with $H \to VV \to 4l$ decay
  - Amplitudes parametrised with anomalous couplings → later mapped to Higgs and Warsaw bases

e.g. $$A(\mathrm{HV_1V_2}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_{\mathrm{Q}}^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$



- **Production modes separated according to kinematic features of associated particles**
  - Matrix element approach used to find optimum discriminating variables (sig/bkg and SM/BSM)

Channels	Coupling	Observed	Expected	Observed correlation			
				δc_z	c_{zz}	$c_{z\Box}$	$\tilde{c}_{zz}$
VBF & VH & H $\to 4\ell$	δc_z	$-0.03^{+0.06}_{-0.25}$	$0.00^{+0.07}_{-0.27}$	1	+0.241	−0.060	−0.009
	c_{zz}	$0.01^{+0.11}_{-0.10}$	$0.00^{+0.22}_{-0.16}$		1	−0.884	+0.058
	$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$			1	+0.020
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$				1

Higgs basis

- **Extended maximum likelihood fit using μ_i and fractional coupling contributions**

e.g. $$f_{ai}^{\mathrm{VV}} = \frac{|a_i^{\mathrm{VV}}|^2 \alpha_{ii}^{(2e2\mu)}}{\sum_j |a_j^{\mathrm{VV}}|^2 \alpha_{jj}^{(2e2\mu)}} \,\mathrm{sign}\left(\frac{a_i^{\mathrm{VV}}}{a_1}\right)$$

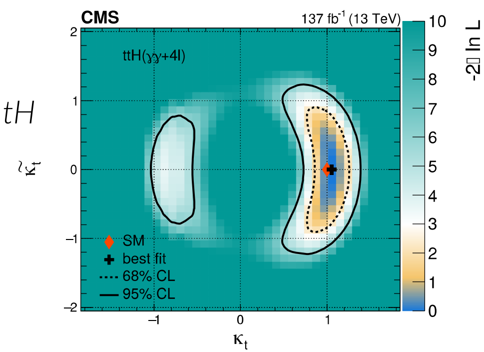
  - Use assumptions on Higgs width to get constraints on couplings

Results consistent with SM Higgs

$tH + ttH + ggH$

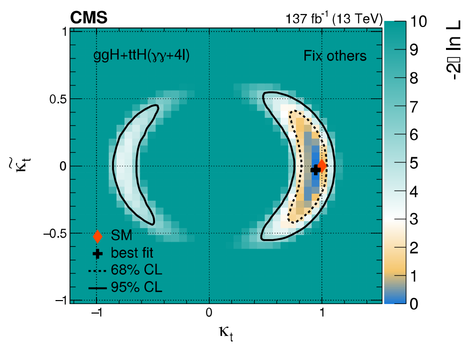
137 fb^{-1} [arXiv:2104.12152]

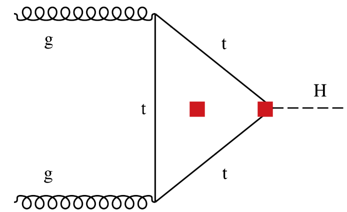
- **New approach to resolving operators affecting *ggH* loop**
  - Combination of measurements for *tH*, *ttH* and *ggH* processes (including $H \to \gamma\gamma$ contribution to *tH* and *ttH*)
  - Four coefficients affecting *ggH* loop can be resolved → pointlike interaction $\boldsymbol{c_{gg}}$, *Htt* coupling $\boldsymbol{\kappa_t}$ + CP-odd variants
- **Processes provide complementary information** → allows resolution of ambiguities in likelihood scan, e.g. *tH* excludes negative κ_t , *ggH* resolves +/- values of $\tilde{\kappa}_t$,

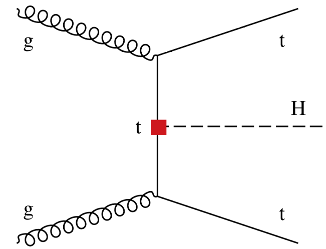


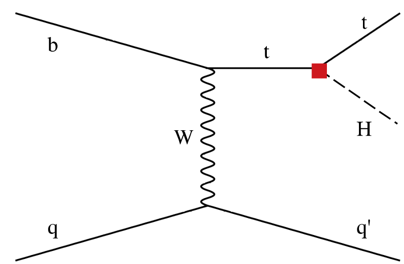
$ttH + tH$

$+\ ggH$









Channels	Coupling	Observed	Expected	Observed correlation			
				c_{gg}	$\tilde{c}_{gg}$	κ_t	$\tilde{\kappa}_t$
tH & $t\bar{t}$H & ggH	c_{gg}	$-0.0012^{+0.0022}_{-0.0174}$	$0.0000^{+0.0019}_{-0.0196}$	1	-0.050	-0.941	$+0.029$
	$\tilde{c}_{gg}$	$-0.0017^{+0.0160}_{-0.0130}$	$0.0000^{+0.0138}_{-0.0138}$		1	$+0.046$	-0.568
	κ_t	$1.05^{+0.25}_{-0.20}$	$1.00^{+0.34}_{-0.26}$			1	$+0.168$
	$\tilde{\kappa}_t$	$-0.01^{+0.69}_{-0.67}$	$0.00^{+0.71}_{-0.71}$				1

↑ $ttH(\gamma\gamma + 4l)$

Higgs basis

Results consistent with SM Higgs

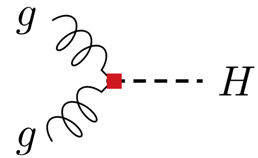
Higgs combination

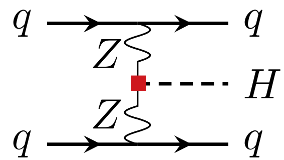
ATLAS EXPERIMENT

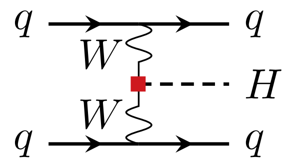
139 fb^{-1}

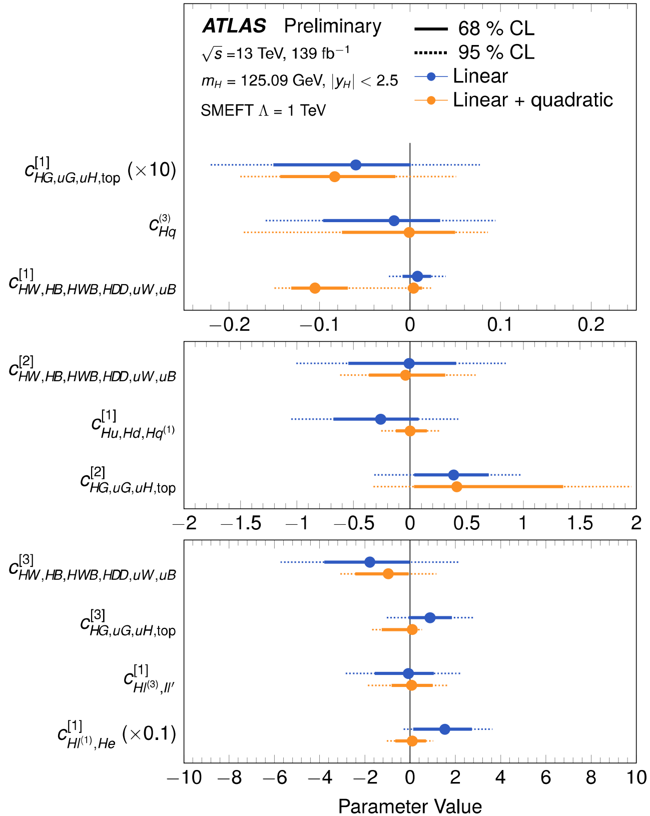
[ATLAS-CONF-2020-053]

- Combine $H \to \gamma\gamma$, $H \to ZZ \to 4l$ (all production modes) and $H \to b\bar{b}$ (VH) measurements
  - Separate measurements performed using STXS framework (STXS 1.1/1.2) → combine measurements for processes in joint likelihood









- 32 Wilson coefficients in Warsaw basis with significant impact
  - Signal strength modifiers expressed with linear terms only or linear + quadratic terms
  - Find most sensitive directions with grouping of c_i by physics impact → eigenvectors and eigenvalues in each group
  - 10 sensitive directions used

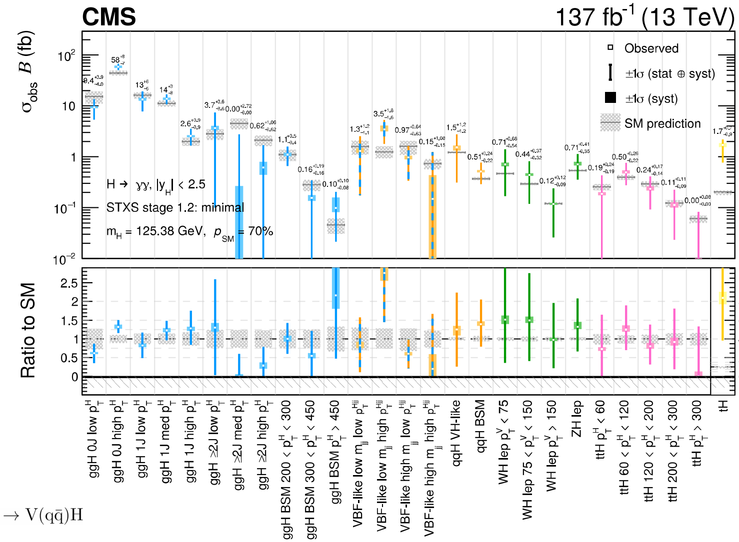
Observations consistent with SM, and generally tighter constraints with quadratic model

$H \to \gamma\gamma$, $H \to 4l$

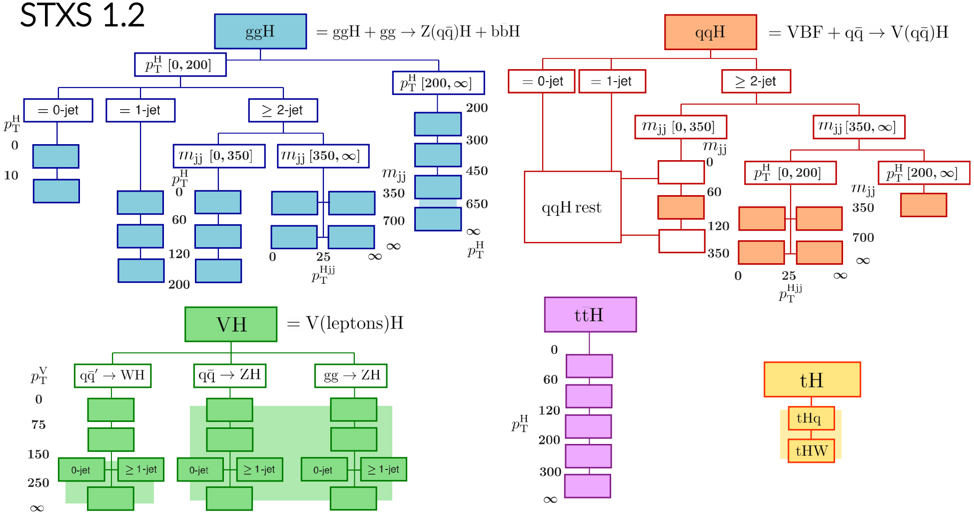
- First set of STXS 1.2 measurements in two golden Higgs channels

$H \to \gamma\gamma$ **137 fb^{-1}** [arXiv:2103.06956]

- Measurements of μ inclusively and per production mode
- Cross sections for maximal (17) and minimal (27) merged STXS 1.2 bins
  - Many regions measured for first time, e.g. ttH in 5 different regions of p_T^H



STXS 1.2



$H \to 4l$ **137 fb^{-1}** [arXiv:2103.04956]

- Measurements of μ inclusively and per production mode
- Cross sections obtained for 19 merged STXS 1.2 bins

Measurements consistent with SM, very relevant for EFT in future

Contents

Electroweak measurements

$pp \to 4l$, $W\gamma$, WW, WZ, $V\gamma\gamma$, $Z\gamma jj$

Higgs measurements

$H \to 4l$, $H \to \gamma\gamma$, Higgs combinations

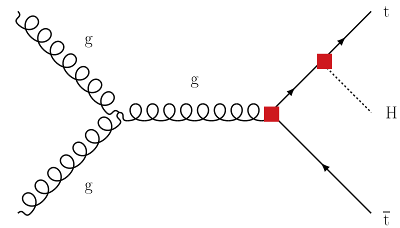
Top measurements

$t(t)$ + leptons, $tt\gamma$

$t(t)$ + leptons

41.5 fb^{-1}

[arXiv:2012.04120]

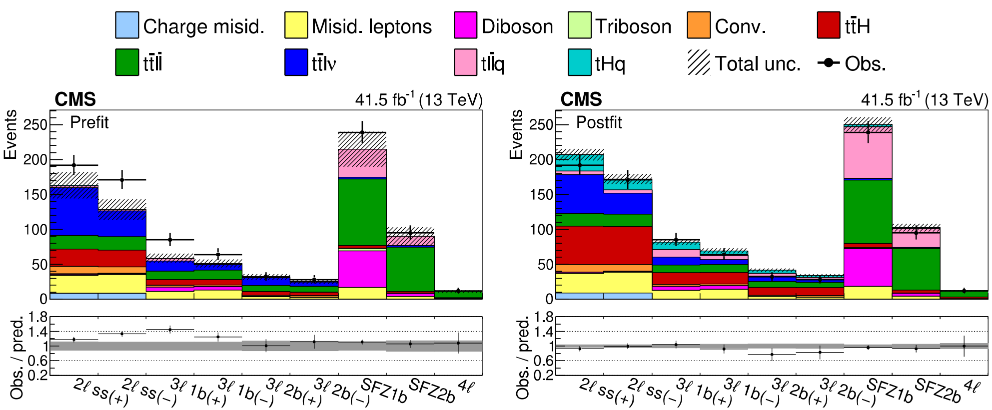


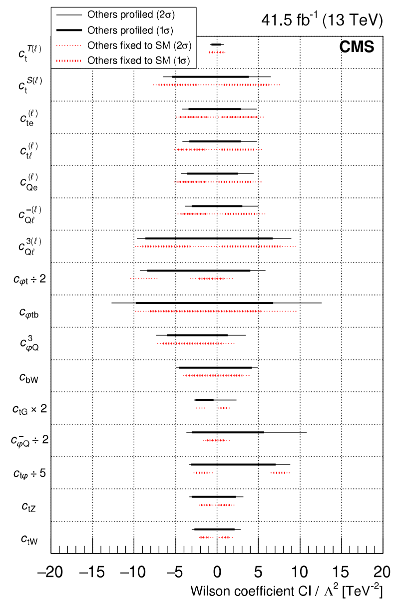
- Dedicated EFT measurement → fit performed on detector level
  - Five signal processes considered → *ttH*, *ttll*, *ttlv*, *tllq*, *tHq*
- Events categorised based on leptons and (*b*-)jets → 35 non-overlapping SRs
- 16 operators considered → chosen because of expected large impact on signal processes but not backgrounds
  - Parametrise signal event weights with c_i →

$$w_i\left(\frac{\vec{c}}{\Lambda^2}\right) = s_{0i} + \sum_j s_{1ij}\frac{c_j}{\Lambda^2} + \sum_j s_{2ij}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} s_{3ijk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2},$$

- Maximum likelihood fit performed across all SRs
  - Two fits performed: all c_i profiled; setting all but one c_i to zero

Consistent with SM at level of 2σ or better

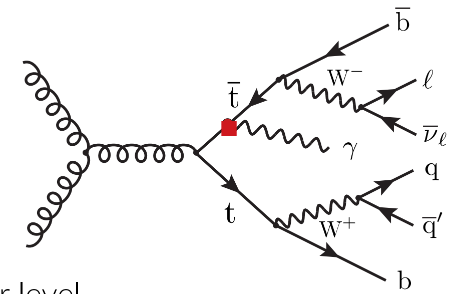




$t\bar{t} + \gamma$

137 fb^{-1} [TOP-18-010]

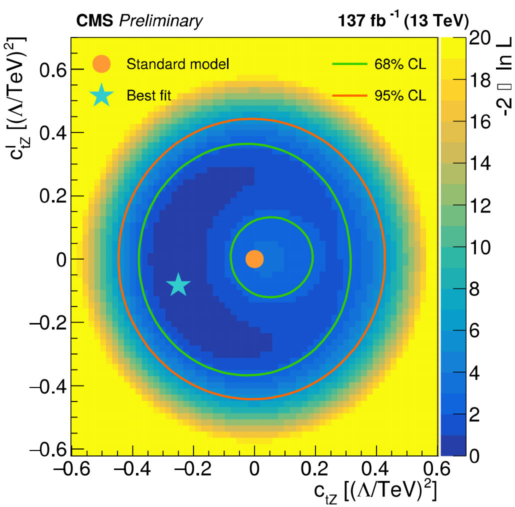
- Inclusive and differential cross section measurements in single lepton channel

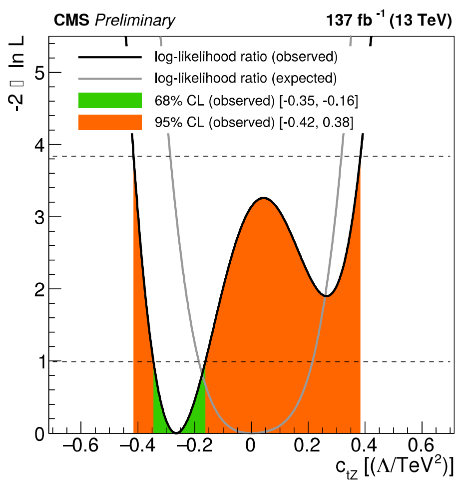


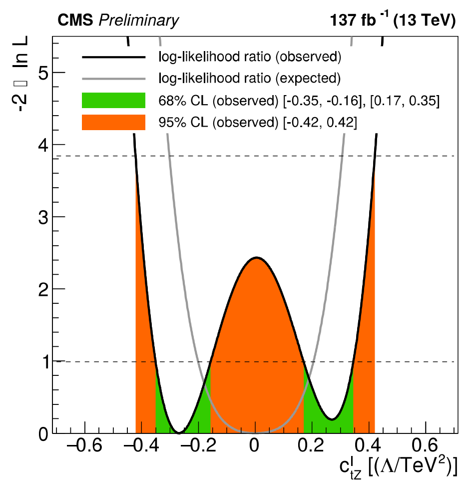
- Anomalous top quark electroweak dipole moments affect $t\gamma$ vertex
  - Effects parametrised by Wilson coefficients c_{tZ} and c_{tZ}^{I}
- Constrain coefficients using $p_T(\gamma)$ on detector level
  - Reweight SM samples using SMEFT/SM weights obtained on generator level
- Maximum likelihood fit performed → best constraints to date

Data set	Wilson coefficient	68% CL interval	95% CL interval
expected	c_{tZ}	[-0.19, 0.21]	[-0.29, 0.32]
	c_{tZ}^{I}	[-0.20, 0.20]	[-0.30, 0.31]
observed	c_{tZ}	[-0.35, -0.16]	[-0.42, 0.38]
	c_{tZ}^{I}	[-0.35, -0.16], [0.17, 0.35]	[-0.42, 0.42]

Consistent with SM at level of 2σ or better







Additional measurements

- Many additional measurements potentially relevant for future EFT interpretations (listed here only full Run 2 measurements since October 2020)

Electroweak

CMS: $Z + c$-jets [arXiv:2012.04119] – April 2021

ATLAS: $\gamma\gamma \to WW$ [arXiv:2010.04019] – October 2020

Higgs

CMS:

$VH(WW)$ [HIG-19-017] – March 2021

$t(t)H$ [arXiv:2011.03652] – November 2020

ATLAS:

$H \to WW$ [ATLAS-CONF-2021-014] – March 2021

$H \to bb$ [ATLAS-CONF-2021-010] – March 2021

$ttH(bb)$ [ATLAS-CONF-2020-058] – November 2020

Top

CMS: $t\bar{t}$(lepton + jets) [TOP-20-001] – March 2021

ATLAS:

ttZ [arXiv:2103.12603] – March 2021

$t\bar{t}t\bar{t}$ [ATLAS-CONF-2021-013] – March 2021

Summary

- Many interesting analyses relevant for EFT measurements (including many not shown today)
    - EWK, Top, Higgs measurements sensitive to wide range of EFT parameters (both dim. 6 and dim. 8)
    - Measurements specifically target EFT effects or reparametrise distributions
    - Some combinations in Higgs and EWK sector to improve sensitivity → first steps towards global fits
- Limits on EFT coefficients improving, but no deviations from SM yet
    - Large impact of quadratic terms in some analyses potential issue, but new methods for improving sensitivity to linear terms investigated

Backup

$WW + H(WW^*)$

36 fb^{-1} [ATL-PHYS-PUB-2021-010]

- Full complementarity between *WW* and *H*(*WW**) measurements